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JULY, 1920

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DISPERSION IN OPTICAL GLASSES. II.

BY

F. E. WRIGHT.

CERTAIN linear relations between the partial dispersions of optical glasses are emphasized in the first paper of this series;[1] and from these relations several new two- and three-constant dispersion formulas are developed which represent the dispersion curves in the visible spectrum with a high degree of exactness. Reference is also made in that paper incidentally to certain other approximately straight-line relations which were first noted by Sellmeier[2] in 1871, and proved to be theoretically important because they indicated to him the significance of absorption bands in the ultra-violet and the infra-red on the course of dispersion in the visible spectrum. Sellmeier plotted, for a series of optical glasses, the refractive indices against the squares of the reciprocal of the wave length ($1/\lambda^2$, frequency squared) and found that the dispersion curves of many types of optical glass exhibit an inflection point in the visible spectrum, with the result that over this range the general shape of the curve approximates a straight line.

The dispersion relations in different types of optical glass are shown graphically in Figs. *1a*, *1b*. The optical constants of these

[1] *J. Opt. Soc. America*, 4, 148–159, 1920.

[2] *Ann. d. Phys. und Chem.*, 143, 272, 1871.

Schott glasses were measured by H. Rubens and H. T. Simon [3] in the infra-red, the visible, and the ultra-violet. In Fig. 1*a* the refractive indices for the several wave lengths are plotted against wave lengths directly; in Fig. 1*b*, the ordinates are, as in Fig. 1*a*, the refractive indices, while the squares of the frequency, $1/\lambda^2$, are plotted as abscissæ. In both figures, and especially in Fig. 1*b*, the effects of the presence of absorption bands in the ultra-violet and in the infra-red are clearly shown.

The Sellmeier method of plotting refractive indices, n_D, against $1/\lambda^2$ was later adopted by Pulfrich [4] in his work on the change, with temperature, of the dispersion relations in optical glasses.

Under these conditions of plotting the dispersion curve may be assumed to be a straight line for the short range of the visible spectrum and the two-constant Cauchy-formula

$$n = A + B/\lambda^2 \tag{1}$$

or

$$n - 1 = A' + B/\lambda^2$$

is the mathematical expression for this relation.

If now in these equations the reciprocal of the refractive index $\left(\frac{1}{n}\right)$ or of the excess refractivity $\left(\frac{1}{n-1}\right)$ be substituted for the refractive index or the effective refractivity, the dispersion curves become rectangular hyperbolas ($1/\lambda^2$ being considered the independent variable), which, however, do not depart much from a straight line because of the relatively short range of the visible spectrum. The result is that the equations

$$\frac{1}{n} = E + \frac{F}{\lambda^2} \tag{3}$$

$$\frac{1}{n-1} = C + \frac{D}{\lambda^2} \tag{4}$$

are fairly satisfactory dispersion formulas. Equation (4) was suggested recently by P. G. Nutting [5] as a substitute for the three-constant Hartman or Cornu equation

$$(n - n_0)(\lambda - \lambda_0) = C.$$

---

[3] *Ann. d. Phys. und Chem.*, N. F., **45**, 238, 1892; **53**, 555, 1894.

[4] *Ann. d. Phys. und Chem.*, **45**, 648, 1892. See also Hovestadt, *Jenaer Glas*, pp. 46–48. Jena, 1900.

[5] *Rivista d'Ottica e Meccanica di Precisione*, I, 54–57, 1919.

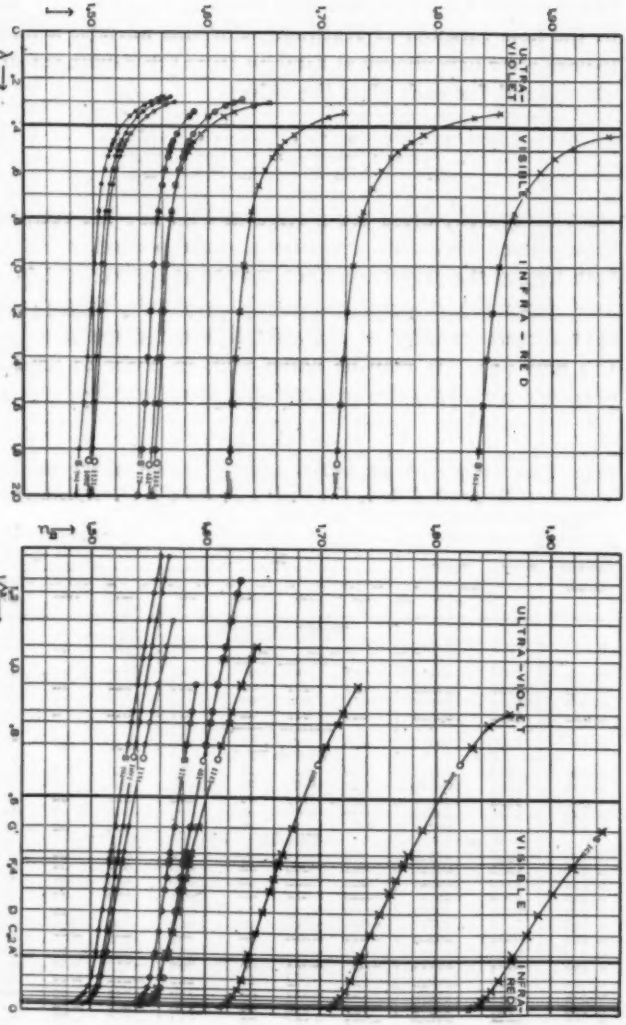

FIG. 1.

In this figure the refractive indices for different wave-lengths in the infra-red, visible, and ultra-violet, as measured by H. Rubens and H. T. Simon on a series of Schott glasses are plotted as ordinates against the wave lengths as abscissæ.

In this figure the abscissæ scale has been changed from the direct wave-length scale (λ) of Fig. 1a to that of the square of the frequency ($1/\lambda^2$). The refractive indices are the ordinates. By this method of plotting, the inflection point of the dispersion curves in the visible spectrum is clearly shown as a result of the absorption band in the ultra-violet and also in the infra-red.

It is of interest, therefore, to compare the accuracy of the old two-constant Cauchy dispersion formula (equation 1) with that of the new formula of Nutting. For this purpose a number of glasses were first chosen at random from the Schott list of optical glasses and for each glass the values

$$\frac{n_C - 1}{n_{A'} - 1}, \quad \frac{n_D - 1}{n_{A'} - 1}, \quad \frac{n_F - 1}{n_{A'} - 1}, \quad \frac{n_{G'} - 1}{n_{A'} - 1}$$

were computed; these are plotted in Fig. *2a;* the reciprocals of these values were also computed and are plotted in Fig. *2b*. In both figures the dispersion lines radiate as approximately straight lines from the A'-point on the abscissa axis, thus proving the approximate validity of the two different dispersion formulas, (1) and (4). It may be noted that, in order to have all dispersion curves pass through a single point, namely, the A'-point,

TABLE I.

In this Table the differences between the tangents of the slope angles of the chords drawn between the points A′ to C, C to D, D to F, and F to G′, respectively on the dispersion curve of each glass, are listed.

Type of Glass	$n_D - 1$	$\frac{n_F - n_D}{1/\lambda^2_F - 1/\lambda^2_D}$	Ia $n_C - n_A$ .00	Ia $n_D - n_C$ .00	Ia $n_F - n_D$ .000	Ia $n_{G'} - n_F$ .00	Ib $n_C - n_{A'}$ .00	Ib $n_D - n_C$ .000	Ib $n_F - n_D$ .000	Ib $n_{G'} - n_F$ .00
				Borosilicate Crown.						
O 144	.5100	.00365	.083	.062	00	−002	026	20	00	−006
				Ordinary Crown.						
O 40	.5166	.00441	025	012	00	005	037	47	00	−004
O 709	.5128	.00466	030	007	00	007	044	16	00	−008
O 608	.5149	.00492	015	004	00	013	030	13	00	001
O 381	.5262	.00538	020	−011	00	017	038	0	00	004
				Barium Crown.						
O 227	.5399	.00472	026	012	00	006	039	20	00	−004
				Barium Flint.						
O 602	.5676	.00561	016	000	00	014	034	10	00	001
O 543	.5637	.00584	012	−001	00	021	032	10	00	006
O 522	.5554	.00606	006	−007	00	024	027	06	00	008
O 578	.5825	.00659	000	−007	00	029	023	07	00	010
O 1266	.6042	.00726	−005	−011	00	038	024	05	00	015
				Flint Series.						
O 726	.5398	.00599	005	−004	00	024	026	09	00	007
O 378	.5473	.00626	001	−006	00	030	023	08	00	012
O 154	.5710	.00697	−003	−009	00	039	022	07	00	017
O 340	.5774	.00735	−009	−014	00	044	020	03	00	020
O 318	.6031	.00831	−019	−023	00	055	015	−02	00	025
O 118	.6129	.00875	−030	−022	00	063	006	01	00	030
O 103	.6202	.00902	−033	−026	00	067	005	−01	00	032
O 102	.6489	.01014	−049	−034	00	084	−003	−04	00	042
O 199	.6734	.01114	−065	−044	00	098	−011	−11	00	048
O 41	.7174	.01293	−091	−065	00	122	−025	−23	00	059
O 165	.7541	.01460	−124	−082	00	150	−043	−29	00	074
O 198	.7782	.01568	−136	−096	00	179	−047	−30	00	084
O 57	.9026	.02299	−272	−184	00	314	−126	−88	00	166
				Silica Glass.						
	.4585	.00347	041	040	00	−005	67	28	00	−010

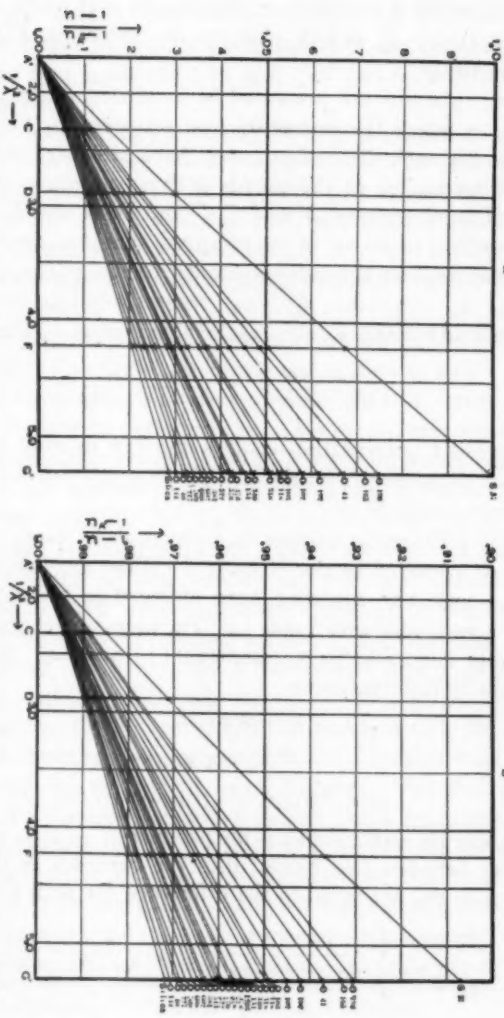

FIG. 2.

In this figure the ratios $(n_F-1)/(n_d-1)$ for a series of Schott glasses are plotted as ordinates against the squares of the frequency $(1/\lambda^2)$ as abscissæ.

The reciprocal ratios $(n_d-1)/(n_F-1)$ are plotted as ordinates against the same abscissæ scale $(1/\lambda^2)$. The series of glasses represented in these figures are the same as those listed in Table I and include all types of silicate glasses. These figures demonstrate clearly the feasibility of substituting in the Cauchy dispersion formula $1/(n-1)$ for $(n-1)$ and thus obtaining the Nutting formula.

each value of the excess refractivity $(n-1)$ was divided by $(n_{A'}-1)$, while in the series of reciprocals each value was multiplied by $(n_{A'}-1)$ before plotting the values in Fig. 2*a*, and 2*b*, respectively.

These relations are presented in somewhat different form in Table I, in which the procedure first proposed by Sellmeier [6] is adopted; for each dispersion curve there are listed the tangents of the slope angles of the chords drawn between certain points on the dispersion curve A' and C, C and D, D and F, F and G', respectively. Table I*a* is so arranged that for each glass the differences between the values obtained for the partial dispersions $n_C - n_{A'}$, $n_D - n_C$, and $n_{G'} - n_F$, respectively, are listed. Thus in the column headed $n_D - n_C$ each value is equal to the difference

$$\frac{n_F - n_D}{1/\lambda^2_F - 1/\lambda^2_D} - \frac{n_D - n_C}{1/\lambda^2_D - 1/\lambda^2_C}.$$

This form of presentation enables the eye to note readily the degree of departure from the straight-line relation for which all differences would be nil.

In Table I*b* similar data on the reciprocals of the excess refractivities, as required in the Nutting formula, are listed. In this table the scale has, however, been changed in order to make it directly comparable with Table I*a*. The necessary changes in scale are readily deducible from equations (1) and (4), from which we obtain by differentiation

$$dn = B.d(1/\lambda^2)$$

$$-\frac{dn}{(n-1)^2} = D.d\,(1/\lambda^2)$$

or

$$dn = B.d(1/\lambda^2) = -D.\,(n-1)^2\,d(1/\lambda^2).$$

In Table I*b*, each number is the product of $-(n_D-1)^2$ and the difference between two ratios; thus the numbers in the column headed $n_C - n_A$ are equal to the difference for each glass,

$$-(n_D-1)^2.\left\{\frac{\frac{1}{n_F-1}-\frac{1}{n_D-1}}{\frac{1}{\lambda^2_F}-\frac{1}{\lambda^2_D}} - \frac{\frac{1}{n_C-1}-\frac{1}{n_{A'}-1}}{\frac{1}{\lambda^2_C}-\frac{1}{\lambda^2_{A'}}}\right\}$$

[6] *Ann. d. Phys. und Chem.*, **143**, 272, 1871.

The order of magnitude of the values listed in Tables I*a* and I*b* is accordingly directly comparable, as a first approximation, and the relative degree of exact representation of the dispersion relations by the two equations (1) and (4) can be ascertained by direct inspection.

Table I demonstrates that for the crown glasses as a whole (ordinary crowns, borosilicate crowns, barium crowns) the Cauchy formula is superior to the formula proposed by Nutting, whereas for the flint series and the barium flints the Nutting formula is somewhat better; but even in this case the agreement of the values computed by the Nutting formula with the observed values is not close.

It is, of course, possible, even in cases where the calculated values depart from the observed values, to obtain, either graphically or by computation, a curve of departures or errors (residuals) and from it to ascertain the value of the refractive index for any intermediate wave length to a high degree of exactness.

To test still further the relative accuracy of equations (1) and (4), the residuals for the four glasses cited by Nutting[7] were computed for each equation. These glasses were measured with a high degree of precision by Gifford[8] and include a telescope crown *S* 3418 ($n_D = 1.530848$, $\nu = 60.6$), a dense barium crown *S* 4704 ($n_D = 1.610702$, $\nu = 55.7$), a dense flint *C* 629 ($n_D = 1.612137$, $\nu = 37.0$), and a borosilicate flint *S* 3338 ($n_D = 1.548146$, $\nu = 49.9$). For each one of the four glasses the constants of the equations (1) and (4) were computed by the method of the Zero Sum recently proposed by N. Campbell[9] as an improvement on the method of Least Squares. For this purpose twelve of the thirteen refractive indices listed by Gifford were used; the refractive indices for the wave length 0.4415μ were not used as they differ only slightly from those for wave length 0.4341μ and their exclusion facilitated the computations. The resulting equations for the several glasses are given in Table II.

The equations II of Table II are built up from the refractive

[7] *Revista d'Ottica a Meccanica di Precisione I*, 56, 1919.
[8] *Proc. Roy. Soc.*, 87, 190–191, 1912.
[9] *Phil. Mag.*, 39, 177, 1920.

indices by computing first the reciprocal of the excess refractivity for each refractive index $\left(\frac{1}{n-1}\right)$; from this list of reciprocals the constants of the equation are obtained by the Campbell method of the Zero Sum. The values $\frac{1}{n-1}$ are then computed from the equation II thus obtained and the values of the reciprocals of these in turn are computed and compared with observed values.

The differences between computed and observed values as found from the two equations I and II are listed in Table III. There is also included in this table a series of values computed for the telescope crown *S* 3418, according to the plan adopted by Nutting, namely, to compute for each glass the values *A'* and *B*

TABLE II.

	I.	II.
S 3418	$n=1.517485+\frac{0.0046242}{\lambda^2}$	$\frac{1}{n-1}=1.930798-\frac{0.0162097}{\lambda^2}$
S 3418	$n=1.517593+\frac{0.0046031}{\lambda^2}$	$\frac{1}{n-1}=1.929846-\frac{0.0159981}{\lambda^2}$
S 4704	$n=1.594036+\frac{0.0057836}{\lambda^2}$	$\frac{1}{n-1}=1.681725-\frac{0.0152994}{\lambda^2}$
C 629	$n=1.586814+\frac{0.0088606}{\lambda^2}$	$\frac{1}{n-1}=1.700146-\frac{0.023137}{\lambda^2}$
S 3338	$n=1.531396+\frac{0.0058158}{\lambda^2}$	$\frac{1}{n-1}=1.879484-\frac{0.0190631}{\lambda^2}$

or *C* and *D* of the two equations from the two refractive indices n_D and $n_{G'}$. In this case the departures are slightly greater than with the better adjusted constants, but the order of magnitude of the values is the same.

Table III proves definitely that in the two crown glasses the differences between computed and observed values are less for the Cauchy formula (equation 1) than for equation (4), while in the two flint glasses the departures are less for equation (4).

The foregoing different lines of approach prove definitely that in certain cases, namely the crown glasses, equation (1) furnishes values more nearly in agreement with the data of observation than does equation (4); that in the flint glasses, on the other hand, equation (4) is superior to equation (1), but that even with equation (4) the results of computation differ appreciably from

the observed values and that neither equation (1) nor (4) represents the data of observation in the flint series with a high degree of precision.

The Nutting formula (equation 4) is less convenient for purposes of computation than the Cauchy formula (equation 1); and in view of the fact that it is superior to the Cauchy formula only for the flint glasses, its use for general purposes as a substitute for the Cauchy and the Hartman formulas, does not seem

TABLE III.

In this Table are listed, for four Schott glasses measured by Gifford, the residuals (differences between computed and observed values) of refractive indices for different wave lengths from the Cauchy dispersion formula (Columns I) and the new formula suggested by Nutting (Columns II). In Columns I′ and II′ are listed the residuals for a straight line passing through D and G′.

Wave length	Telescope Crown S 3418				Dense Barium Crown S 4704		Dense Flint C 629		Borosilicate Flint S 3338	
	I .0000	II .000	I′ .000	II′ .000	I .000	II .000	I .00	II .000	I .000	II .000
.7682	90	164	162	275	078	179	−0242	−002	058	172
.7066	17	048	082	195	−018	025	−0138	−033	−036	014
.6708	−13	−009	048	126	−010	−001	−0067	−043	−027	−017
.6563	−27	−032	032	097	−038	−043	−0043	057	−044	−050
.5893	−47	−093	000	000	−011	−078	0192	038	−003	−078
.5607	−17	−080	025	−001	−001	−087	0286	086	052	−047
.5461	−25	−093	012	−024	007	−084	0329	113	068	−035
.5270	−07	−063	039	−009	037	−059	0350	124	079	−029
.4861	45	−010	063	−006	052	−022	0330	149	081	−003
.4678	32	−002	043	−006	047	001	0238	123	075	024
.4415	07	031	007	−009	030	062	−0056	006	014	038
.4341	04	050	000	000	−001	062	−0214	−080	033	036
.4046	−60	125	081	023	−143	108	−1036	−461	−271	011

advisable; to substitute it for the ordinary three-constant Hartman formula, $(n-n_0)(\lambda-\lambda_0)^{1.2}=C$, does not lead to equally satisfactory results.

SUMMARY.

In this paper, proof is given that, because of the relatively short range of the visible spectrum, the substitution in a dispersion formula of the reciprocal of the refractive index or of the excess refractivity or, by analogy, of other functions of the refractive index in place of the direct values, leads to dispersion formulas which are fairly satisfactory. Thus, if in the two-constant Cauchy formula, $n=A+B\lambda^{-2}$ or $n-1=A'+B\lambda^{-2}$, the reciprocal of the refractive index or of the effective refractivity be

written: $n^{-1} = C' + D'.\lambda^{-2}$ or $(n-1)^{-1} = C + D.\lambda^{-2}$, the new equations represent rectangular hyperbolas in case λ^{-2} is considered to be the independent variable. The last equation was recently suggested by Nutting as a substitute for the Hartmann dispersion formula. A series of computations demonstrates, however, that for the crown glasses this equation is less satisfactory than the Cauchy formula, while for the flint glasses, none of the foregoing equations is especially good. The last equation is, moreover, always less satisfactory than the Cauchy formula for computation purposes; its usefulness appears, therefore, to be limited and less satisfactory for general application than the two-constant Cauchy formula.

GEOPHYSICAL LABORATORY,
CARNEGIE INSTITUTION OF WASHINGTON,
June, 1920.

CLASSIFICATION AND NOMENCLATURE OF OPTICAL GLASS.[1]

BY

GEORGE W. MOREY.

A STUDY of the optical glass catalogues of the various American and foreign manufacturers reveals a striking lack of uniformity in nomenclature. The names in use are the result of a gradual development, in the course of which each manufacturer has listed new glasses, as they have been developed, under names which seemed appropriate. The natural result of this haphazard method has been that in some cases the same glass is known by several different names; in other cases, glasses differing in no essential property from the usual types have received names implying the possession of special properties which the glasses do not possess in any marked degree. Furthermore, the nomenclature adopted by any one manufacturer has rarely been consistent; witness the confusion between the so-called "soft crowns," "crowns of high dispersion," "extra light flints," and "telescope flints." Indeed, there is apparently inextricable confusion between the broad general classes of the crowns and the flints.

It has been the purpose of the writer to simplify the nomenclature of optical glass by the elimination of many of the special names, retaining only names which, while indicating the position of the glass in the general scheme, leave its precise specification to be indicated by its optical properties. There are two objections which might be urged against this procedure. In the first place, it might be claimed that this means the obliteration of types chemically distinctive, such, for example, as the borate flints or zinc crowns. It should be noted in this connection, however, that such distinctions are far less real than has commonly been believed. The difference between a "zinc crown" and an ordinary crown is not one of fundamental difference in type; indeed, many ordinary crowns contain zinc oxide, introduced more for its

[1] An extract from the Report of the Subcommittee on Optical Glass, Nomenclature and Standards Committee, American Optical Society, presented at the New York meeting, February 27–28, 1920.

effect on the manufacturing process than for its effect on the optical properties. Similarly, the borate flints do not differ significantly from the barium flints, to which they are in many respects inferior; they have been but little used and their manufacture has become less common. These conclusions are at variance with the views often found in the literature, but are fully substantiated by the work of Wright,[2] in which the reader will find further illustrations of the same kind.

The second objection which might be offered to such a plan of nomenclature is that it would lead to confusion in the purchase of optical glass. Quite the contrary is the case. Glass type names are for convenience in casual reference only; purchase always should be on definite specification of the optical properties desired. This point should be strongly emphasized.

The optical constants in common use are the refractive index for sodium light, n_D, and the ν-value, the ratio of the excess refractivity, $n_D - 1$, to the mean dispersion, C to F, $\left(\frac{n_D - 1}{n_F - n_C}\right)$. It is a well-known fact that in the ordinary crown-flint series of glasses, the so-called "older" glasses, the mean dispersion may be expressed as a linear function of the refractive index,

$$(n_F - n_C) = an_D - b$$

and hence the ν-value also may be expressed as a function of the refractive index,

$$n_D = \frac{1 - b\nu}{1 - a\nu}$$

The graph of this equation is shown in Fig. 1. The constants a and b have the values 0.078984 and 0.110887, respectively. In the same figure[3] are plotted all the glasses listed in the catalogues of the Spencer Lens Optical Glass Plant, Glaswerk Schott und Genossen, and Chance Brothers and Co., Limited. It will be observed that a large proportion of the glasses lie on the curve; these are the glasses of the ordinary crown-flint series, on which the proposed system of nomenclature is based. These glasses are essentially mixtures of silica with alkalies, lime, boric acid,

[2] "Dispersion in Optical Glasses." F. E. Wright, *J. Opt. Soc. Amer.*, **4**, 148 (1920).

[3] A somewhat similar figure has been published by Montgomery. *Chem. Met. Eng.*, **21**, 467 (1919).

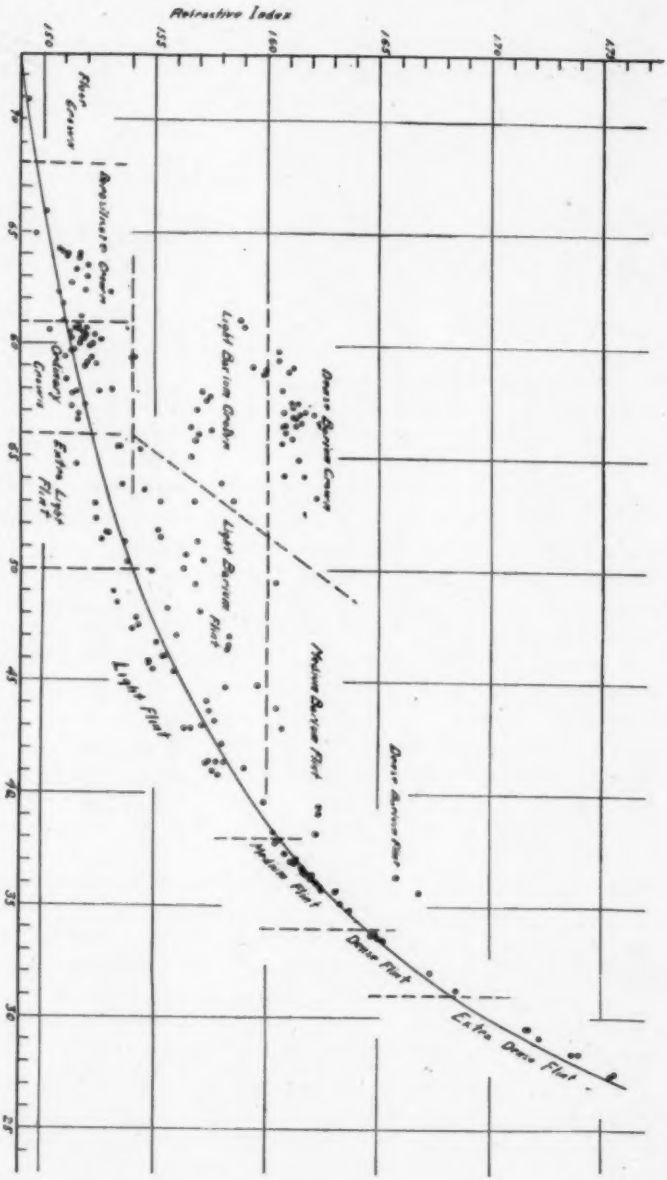

Fig. 1.

Figure showing the suggested classification of optical glasses.

and lead oxide; boric acid and lime characterizing the glasses of lower refractive index, lead oxide, those of higher index. Barium oxide is present only in small amounts, if at all. These glasses will be considered first, after which the barium glasses will be discussed.

The glasses of lowest refractive index and highest ν-value are the fluor crowns. They have a very small dispersion, and are distinctive in type from all other glasses. The lower limit of ν-value for these is 68; glasses of lower ν may contain fluorine, but it is no longer the essential constituent without the use of which glass of the property in question cannot be prepared.

The next group of glasses are the borosilicate crowns. These are characterized by a ν-value lower than the fluor crowns, but higher than the ordinary crowns. As indicated by the name, the characterizing component is boric acid, which in the lower index members of the series is present in large amounts. Their distinctive properties are conferred by boric acid, which, as is well known, is notable for its constraining effect on the spectrum, *i.e.*, for its small dispersive power. It is also present in large amounts in the fluor crowns, but with it alone we are not able to obtain the glasses with the largest ν-value. The dividing line between the borosilicate crowns and the ordinary crowns is placed at a ν-value of 61; boric acid is essential in glasses of higher ν, but, while it may be present in small amounts in glasses of lower ν-value, its presence ceases to be of paramount importance below the limit given.

The next group contains the ordinary crowns, often termed silicate crowns and hard crowns. In this group are included also the zinc crowns, which fall well on the curve.[4] The dividing line between the ordinary crowns and light barium crowns will be referred to later.

A difficult point in optical glass nomenclature is fixing the dividing line between crowns and flints. Historically, the term flint has nothing to do with the chemical composition of the glass, but is derived from the use of flints as a source of silica by the first makers of lead glass. According to present usage, however, a flint glass is one containing lead oxide, and it seems best to retain the term with this explicit significance. Accordingly, the divid-

[4] Compare the position of the zinc crowns in the paper by Wright (*loc. cit.*), Fig. 1.

ing line between crowns and flints in the ordinary crown-flint series has been placed at a ν-value of 56. Lead oxide is an essential constituent of all glasses of this series, and a ν-value of 56 represents fairly closely the dividing line between glasses entirely free from, or containing but small amounts of, lead oxide, and those which cannot be produced without its aid. The same facts are clearly brought out in Fig. 1 of the paper by Wright, to which reference has already been made. Here it will be noticed that glasses of the crown-flint series having the ratio $\frac{n_D - n_{A'}}{n_{G'} - n_F}$ greater than 1.1 are typically free from lead oxide, while those having this ratio less than 1.1 all contain lead.

The flints are sub-divided for convenience into the extra light flints, light flints, medium flints, dense flints and extra dense flints. The dividing line is wholly arbitrary. and represents fairly well established usage.

The first sub-group of flints, the extra light flints, with ν-values from 56–50, contains glasses listed under many different names. It includes some "crowns of high dispersion," some "soft crowns," "telescope flints" and extra light flints. All of these, however, are characterized by containing lead oxide as an essential constituent. Their resemblance to each other, and their proper position in the crown-flint series will be evident from a comparison of their optical properties; this is especially marked in the curves published by Wright,[5] to which reference has frequently been made. It is manifest that no useful purpose is served by continuing this confusion of names, all of which, while implying a higher dispersion than the crowns, also implies a contrast with one another in optical properties which is not justified by the facts.

The next group, the light flints, is one containing a far larger range of index and ν-value than the preceding. The group is one of fairly well-defined properties, special glasses used in small quantity for a wide variety of instruments, but rarely used in large quantity. With the exception of indefiniteness as to the upper and lower limits of the class, catalogues of various firms agree as to the nomenclature of these glasses. The upper limit chosen, a ν-value of 38, corresponds to a flint of index 1.605, which is usually considered as belonging to the next group.

The group of medium flints includes those glasses of the

[5] *Loc. cit.*

crown-flint series having refractive index from 1.60 to about 1.64, ν-values from 38 to 34. The very important flints with index 1.616 and 1.620 are included. The name chosen, medium flints, is expressive of their lead oxide content; they are commonly listed as medium or ordinary flints, though even the 1.616 flint is termed a " dense " flint by some makers.

The group of dense flints here includes those with ν-value from 34 to 31, index from 1.64 to 1.69, while the flints of higher lead content, index 1.70 and higher, are termed extra dense flints. This is in accord with established usage.

We will next consider glasses of totally different composition, the dense barium crowns. These are characterized by the absence of alkali, and by their large content of barium oxide, oftentimes 40 to 50 per cent.; other components are boric acid, zinc oxide, alumina and silica. Optically they have the refractive index of a medium flint, from 1.60 to 1.62 or higher, with the ν-value of a crown, usually greater than 56, though they may have a ν-value as low as 53 without the presence of lead oxide. These glasses are one of the triumphs of the application of modern science to the art of glass-making, and they have made possible the modern high-speed anastigmatic lenses so extensively used in photography to-day.

By the introduction of alkalies into the dense barium crowns we may obtain the light barium crowns, intermediate in composition and optical properties between the dense barium crowns and the ordinary crowns. Almost any desired glass intermediate between these two may be obtained, though only a few have any commercial importance. The actual boundary line between the light barium crowns and the dense barium crowns, on one hand, and the ordinary barium crowns on the other is, of necessity, somewhat arbitrary; in the boundaries selected I have been guided by the absence of alkalies in the dense barium crowns, and the great importance of barium oxide in the light barium crowns, as contrasted with its relatively slight importance, when present, in the ordinary crowns. Accordingly, the light barium crowns have been defined as including those glasses having refractive index between 1.600 and 1.540, and of lower dispersion, *i.e.*, higher ν-value, than the barium flints.

In the ordinary crown-flint series, the boundary between crowns and flints was placed at a ν-value of 56, this representing

fairly well the line of demarcation between glasses in which lead oxide is an essential constituent and those containing no lead oxide. Because of the specific properties of barium oxide, this distinction cannot be made between the barium crowns and barium flints. Practically, however, the distinction is not difficult to make, and a line drawn from the point $nD = 1.54$, $\nu = 56$ and $nD = 1.62$, $\nu = 50$, will serve to separate the lead-free barium glasses from those containing lead oxide in significant amounts.

The definition of the barium flints is based on their relation to the barium crowns and the ordinary flints. From the glass-makers' point of view they are distinctive, lying between the barium crowns, on the one hand, from which they may be distinguished by their lead oxide content, and the flints of the ordinary series, on the other hand, from which they may be distinguished by the presence of barium oxide. The entire series may be considered as derived from the ordinary flints by partial replacement of lead oxide by barium oxide, and this replacement may take place to almost any degree, thus making possible a wide range in composition. Only a comparatively few of the possibilities, however, have proven commercially useful.

Sub-divisions of the barium flints into light, medium and dense have been made for convenience, the dividing lines being at the refractive indices 1.60 and 1.64, respectively; these correspond approximately to the similarly named divisions in the ordinary series.

The classification and grouping of optical glasses which has been outlined provides a systematic and logical system, in which the essential factors in composition have been emphasized in the group names, borosilicate crown, crown, flint, barium crown and barium flint. For further convenience, some of these have been further subdivided, the groups coinciding roughly with the names in common use, which have historical value and have a place in the literature.

As has already been stated, purchase of glass should be on specification of the optical properties desired. For example, if a flint of index 1.616, ν 36.6, is desired, it should not be ordered merely as "ordinary flint glass" or "dense flint glass," but as a flint, or medium flint, index 1.616, ν 36.6, plus or minus such tolerance as is reasonable and proper. Indefinite specifications are a source of confusion, and often lead to annoying delays and errors.

Another plan of nomenclature, which carries out the above principles in a far more extreme degree, is the plan adopted by the new Sendlinger Optical Works, near Berlin. They have discarded all the usual names except crown and flint, and coined the new names "barion" and "barint" to designate the barium crowns and barium flints, respectively. Glasses are designated by a compound numeral, consisting of the first three digits of the refractive index minus 1 ($n_D - 1$), followed by the first two digits of the ν-value, the two parts being separated by a hyphen. This, however, offers but little advantage. It is not noticeably shorter than the system herein proposed, saving only one or two digits, and is less simple and more apt to lead to confusion.

SUMMARY.

The system of optical glass nomenclature proposed is based on the crown-flint series of "older" glasses, *i.e.*, barium-free glasses. The dividing line between crowns and flints is at a ν-value of 56, the approximate lower limit of the lead glasses. The crowns are divided into fluor crowns, with ν-value greater than 68, borosilicate crowns, with ν between 68 and 61, and ordinary crowns, with ν from 61 to 56. The flints are divided into extra light, ν from 56 to 50, light flints, ν from 50 to 38, medium flints, ν from 38 to 34, dense flints, ν from 34 to 31, and extra dense flints. Glasses falling outside the crown-flint series are grouped with the barium crowns and barium flints. The barium crowns have nD higher than 1.60, the light barium crowns have nD between 1.60 and 1.54. The barium flints are divided into light barium flints, nD less than 1.60, medium barium flints, index between 1.60 and 1.64, and dense barium flints.

It is emphasized that optical glass type names are for convenience in casual reference only, and do not imply a specification of optical properties. Whenever reference is made to a definite glass, as opposed to the broad general type, whether in the purchase of glass or in discussion of properties or uses, the reference should be made exact by specifying the optical properties, usually the refractive index for sodium light and the ν-value.

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SPENCER LENS OPTICAL GLASS PLANT,
HAMBURG, N. Y.

A NOTE ON THE ANNEALING OF OPTICAL GLASS.

BY

L. H. ADAMS and E. D. WILLIAMSON.

AN ideal optical glass would fulfil three principal requirements. (1) the glass must be colorless and transparent; (2) it must be chemically homogeneous, that is, free from striæ, "stones" and bubbles; and (3) it must be mechanically homogeneous—free from internal stress. The last of these requirements is a subject which occupied the attention of the authors during a portion of the period of the war-time participation of the Geophysical Laboratory in the manufacture of optical glass, and is the subject which we now propose to discuss. The prevention of internal stress in glass and its removal when present is a problem which requires, for its exact solution, a determination of certain thermal, optical, and elastic constants of the different glasses. As will be apparent later, the stresses are determined by the temperature gradients and therefore a knowledge of the relations between the various factors such as temperature gradients, rate of heating, stress, and annealing temperature is required. Moreover, since stress is usually measured by the change in an optical property—birefringence—the data in the stress-birefringence ratio must also be obtained. Certain of these phases of the subject have already been covered in previous publications from this Laboratory, and the Annealing of Glass is treated in detail in a paper which is now ready for publication in another journal. It has seemed desirable, however, to summarize briefly the salient features of this subject, in so far as they pertain to optical glass, and accordingly in this note the formation of internal strain in glass is discussed, and concrete directions for the practical annealing of optical glass are presented.

The Way in Which Internal Stress Arises.—When a lump of molten glass is cooled quickly it acquires internal stresses and is said to be "strained."[1] Excessive strain cannot be tolerated

[1] It is important to remember that "stress" denotes a force and "strain" the consequent deformation. Stress usually accompanies strain, but the two words, although often interchangeable, are not synonymous.

in any glass, since it renders the glass liable to break when handled or heated again, while in the case of optical glass even a moderate amount of strain causes troublesome warping of finished lenses and prisms. In order to understand how glass becomes strained, it is necessary to recall that at a sufficiently high temperature glass softens and that when soft, internal stresses are relieved by viscous flow. Moreover, any solid body when heated or cooled from the surface acquires a certain temperature gradient,[2] and this temperature gradient induces temporary stresses the direction and magnitude of which depend on the temperature gradient and the dimensions of the solid.[3] Thus, for example, in a slab of glass the surfaces of which are being heated at a constant rate h (in deg. per min.), the stress F at any point is given by the equation

$$F = 4.6\ h\ (a^2 - 3x^2) \tag{1}$$

in which F is in kg/cm^2 and is positive for a tension, a is the semi-thickness (in cm.) of the plate, and x is the distance from the middle. Along the middle, $x = 0$ and the equation reduces to

$$F = 4.6\ ha^2 \tag{2}$$

Thus, in a slab or plate heated at a uniform rate there will be in the middle a tension in all directions parallel to the faces of the plate, and at the surface a corresponding compression, while at a distance from the middle equal to 0.578 of the semi-thickness is a neutral zone, that is, neither tension nor compression. Fig. 1 illustrates the distribution of stress in a slab of glass 2 cm. thick heated at the constant rate of 5° C. per minute.

The corresponding formula for the stresses in a plate due to a sudden change of surface temperature is more complicated. Its general form is the infinite series:

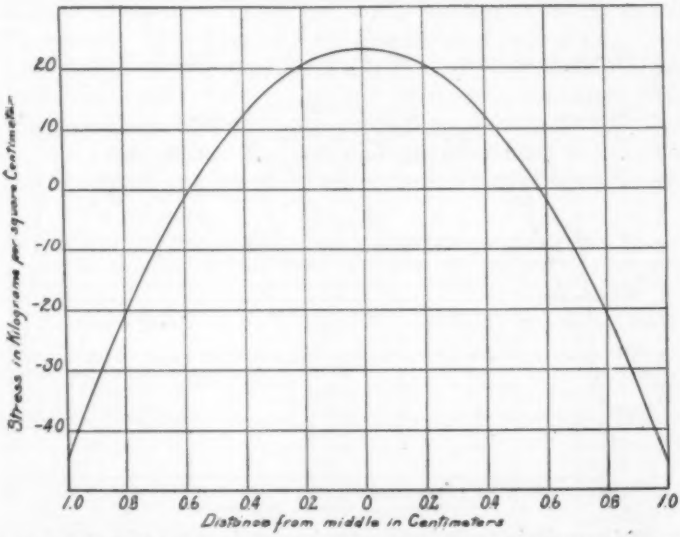
$$F = \frac{4\ a\ (\theta_i - \theta_f)}{\pi\ C} \sum_{m=1}^{m=\infty} e^{-\frac{(2m-1)^2\pi^2 \varkappa t}{4a^2}} \left\{ \frac{2}{\pi(2m-1)^2} - \frac{(-1)^{m+1}}{2m-1} \cos\frac{(2m-1)\pi x}{2a} \right\} \tag{3}$$

[2] E. D. Williamson and L. H. Adams. *Phys. Rev.*, 14, 99–114 (1919).

[3] For a more detailed explanation the reader is referred to the above-mentioned paper on "The Annealing of Glass."

where m is any integer, θi is the initial uniform temperature of the plate, θ_f is the new temperature of the surfaces, C is equal to $\frac{1}{6R} + \frac{2}{9K}$, K being the modulus of compressibility and R the modulus of rigidity, and κ the coefficient of thermal diffusivity. In Fig. 2 is shown for several values of the time, the distribution of stress in a plate of glass 2 cm. thick, initially at 0° C. and suddenly plunged into a bath at 100° C.

FIG. 1.

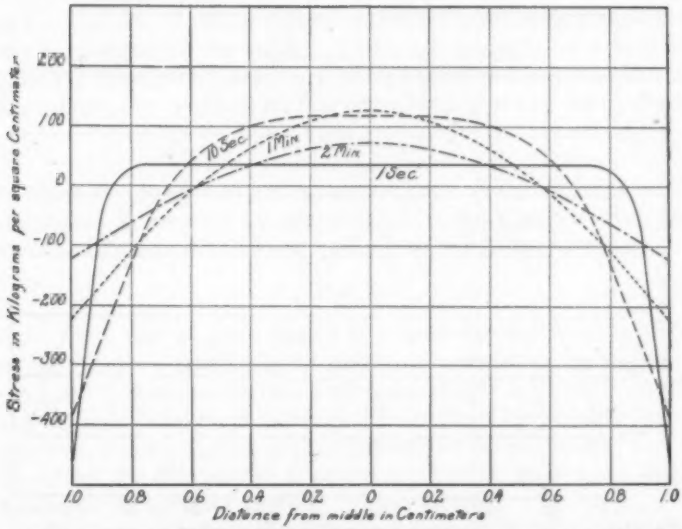


Curve showing distribution of stress in a plate of glass 2 cm. thick which is being heated at a constant rate equal to 5° C. per minute. Stresses are given in kg/cm^2 and are taken as positive for a tension and negative for a compression.

It is obvious that if a temperature gradient happens to exist in a block of glass which is unstrained, the removal of the temperature gradient will produce stresses equal and opposite in sign to those produced by introducing the same gradient. Now if we start with a lump of glass in the molten condition and suppose that it be cooled at a uniform rate, the stresses produced by the establishment of the temperature gradient disappear almost instantly, and as the cooling proceeds we have the condition of a temperature gradient without accompanying stresses. When room

temperature is reached, however, the cooling stops, the temperature gradient disappears, and hence, according to the rule laid down, the removal of the gradient produces a state of permanent stress, which is exactly the same as the system of temporary stresses caused by heating the originally cold and unstrained glass at the same rate. That is to say, if the glass be in the form of a plate, the inside will be in a state of longitudinal tension and

FIG. 2.



Set of curves showing the distribution of stress in a plate of glass 2 cm. thick which, initially at 0° C, is suddenly plunged into a bath at 100° C. The full line indicates the magnitude of the stresses throughout the glass after 1 second has elapsed; the broken line, after 10 seconds; the dotted line, after 1 minute; and the dot-dash line, after 2 minutes.

the outside in a state of longitudinal compression. The same kind of explanation holds for glass cooled at a variable rate and we may perhaps regard the stresses in unannealed glass as due to a temperature gradient (corresponding to a certain cooling rate) being " frozen in " as the glass hardens.

Detection of " Strain."—Glass when subjected to stress becomes birefracting. The usual method for detecting strain takes advantage of this fact, the presence or absence of strain being determined by observing the glass in polarized light between

crossed nicols. A small amount of strain causes a lightening of the field;[4] a larger amount produces the higher colors of the Newton scale, and by comparing the colors with a proper chart a quantitative measure of the optical path difference is obtained. A better method consists in using a graduated quartz wedge[5] in which the path difference can be read directly in $\mu\mu$.

In any one kind of glass the birefringence is proportional to the stress; that is,

$$\Delta n = BF \qquad (4)$$

where F is the stress in kg/cm^2, Δn is the birefringence, and B is a constant. The values of B for nine kinds of optical glass[6] are given in the fourth column of Table I. For most kinds of glass a uni-directional stress of 1 kg/cm^2 produces a maximum birefringence which does not differ much from about 2.8×10^{-7}, that is, about $2.8\mu\mu$ per cm. For heavy flint glasses, however, the value of B is smaller, and for the heaviest flints is of the opposite sign.

TABLE I.

For converting strain from optical to mechanical units. The first three columns describe the glass, and the last column gives the birefringence-stress ratio.

Kind of Glass	Refractive index n_D	Constringence ν	Birefringence due to 1 kg/cm^2 B
Borosilicate Crown	1.516	62	2.85×10^{-7}
Ordinary Crown	1.523	59	2.57×10^{-7}
Light Barium Crown	1.574	57	2.81×10^{-7}
Heavy Barium Crown	1.608	57	2.15×10^{-7}
Barium Flint	1.606	44	3.10×10^{-7}
Light Flint	1.573	42	3.20×10^{-7}
Medium Flint	1.616	37	3.13×10^{-7}
Heavy Flint	1.655	33	2.67×10^{-7}
Extra Heavy Flint	1.756	27	1.22×10^{-7}

Moreover, by determining the sign of the birefringence, that is the α and γ directions,[7] we may know the direction and sign

[4] For detecting a small amount of strain, greater sensitivity is obtained by using a sensitive-tint plate similar to that ordinarily used on the petrographic microscope.

[5] See for example, F. E. Wright. The methods of petrographic microscopic research. Carnegie Inst., Washington, Publication No. 158 (1911).

[6] See L. H. Adams and E. D. Williamson. *J. Wash. Acad. Sci.*, 9, 609–623 (1919).

[7] α is the lesser refractive index, and in a positive uniaxial crystal is for light vibrating perpendicular to the axis.

of stress; thus having determined the α and γ directions (in any ordinary glass), we know that there is either a tension parallel to γ or a compression parallel to α (or both).

Taking the average value of B as $2.8\mu\mu$ per cm., and substituting by equation (4) in equation (2) we have

$$\Delta n = 13\ ha^2 \qquad (5)$$

(in which Δn is in $\mu\mu$ per cm., h is in deg. per min. and a in cm.) for the birefringence along the middle, due to heating a plate of glass at a constant rate.

Removal of Strain—Annealing.—At a sufficiently high temperature the internal stresses relieve themselves by internal movement and thus gradually disappear. If the glass be then properly cooled it will be found to have very little internal strain. We have proposed to call glass "annealed" when the optical path difference[8] as measured along the middle of a slab is not greater than $5\mu\mu$ per cm. The "annealing temperature" is defined as the temperature at which the strain is reduced from 50 to $5\mu\mu$ in a specified time, and the "*annealing range*" is defined, also quite arbitrarily and solely for convenience in referring to this range of temperature, as that 150° interval lying immediately below the "annealing temperature" for 1 minute. Temperature changes below the annealing ranges do not readily affect the permanent strain.

Experimental Determination of Release of Strain.—In order to measure the rate at which stress disappears in various glasses and at various temperatures, rectangular plates of each glass were placed in an electric furnace which was provided with a small hole at either end so that the path-difference (and hence the strain) could be determined *in situ*. The plates were about 2 cm. thick and 8 to 10 cm. long and had the two ends ground flat and then polished.

With each kind of glass measurements were made at several temperatures—usually three—which were measured with a

[8] The standard of annealing proposed by F. E. Wright and adopted during the war for the inspection of optical glass was 20 $\mu\mu$ per cm. *maximum* path difference. The maximum in a slab is found at the outside surface, and is usually about twice that in the middle (where it is easier to measure the strain). Thus $20\mu\mu$ at the surface would correspond to $10\mu\mu$ in the middle. We have preferred the lower value, $5\mu\mu$, because the standard is an arbitrary one in any case, and no difficulty is encountered in annealing glass to that degree of excellence.

platinum-platinrhodium thermocouple in conjunction with a potentiometer. Glass was first strained by rapid cooling from a high temperature and the temperature of the furnace was held constant within 1° while, at frequent intervals of time, the birefringence along the middle of the slab was read by means of a graduated quartz wedge. For further details, including a diagram of the furnace and optical system, the reader is referred to the above-mentioned paper on the Annealing of Glass.

It was found that the release of stress at constant temperature proceeds according to the empirical equation

$$\frac{1}{\Delta n} - \frac{1}{(\Delta n)_0} = At \qquad (6)$$

in which $(\Delta n)_0$ is the original birefringence, Δn is the birefringence at the time t, and A is a constant, which we may call the "annealing constant" for a particular glass at a particular temperature, and which is a measure of the rate at which glass anneals when held at constant temperature. Since by differentiation, $-\frac{d(\Delta n)}{dt} = A(\Delta n)^2$, it is to be noted that the equation (6) is equivalent to the statement that the rate of release of stress at constant temperature is proportional to the *square* of the stress.

The dependence of the rate of annealing on the temperature θ, that is, the relation between A and θ, is expressed by another empirical equation

$$\log A = M_1\theta - M_2 \qquad (7)$$

where M_1 and M_2 are constants. The experimental results are summarized in Table II by giving the values of M_1 and M_2 for

TABLE II.

Constants, M_1 and M_2 of Equation 7, and annealing temperatures for various times.

Kind of Glass.	M_1	M_2	Annealing temperatures.							
			1 min.	5 min.	10 min.	1 hr.	5 hr.	1 day	1 week	1 mo.
Borosilicate Crown....	0.030	18.68	598	575	565	539	515	493	464	444
Ordinary Crown.....	.029	17.35	573	548	538	511	487	464	434	414
Light Barium Crown...	.032	20.10	605	583	574	549	527	506	480	461
Heavy Barium Crown..	.038	24.95	637	619	611	590	572	554	532	516
Barium Flint.....	.028	16.28	555	530	519	491	466	442	412	390
Light Flint.....	.033	15.92	460	439	429	406	385	364	338	320
Medium Flint.....	.038	18.34	463	445	437	416	398	380	358	342
Heavy Flint.....	.037	17.51	453	434	426	405	386	368	345	329
Extra Heavy Flint....	.033	15.03	433	412	403	379	358	337	312	292

each of the nine varieties of optical glass. By means of equation (7) the value of A at a given temperature can be calculated, and from A, by means of equation (6) the "annealing time" for a given temperature can be computed. Thus, recalling that the annealing time is that time in which the birefringence is reduced from 50 to 5$\mu\mu$ per cm., we have by equation (6) that the annealing time

$$t = \frac{\frac{1}{5} - \frac{1}{50}}{A} = \frac{0.18}{A}.$$

The annealing temperature for a given annealing time can be obtained in a similar manner. In making computations by equations (6) and (7) t is to be taken in minutes, Δn in $\mu\mu$ per cm. (10^7 times the true birefringence) and θ in degrees on the Centigrade scale.

Cooling Procedure.—The strain having been removed by holding the glass for a sufficient time at the proper temperature, the next step in the practical annealing of glass consists in cooling it down to ordinary temperatures without reintroducing an excessive amount of strain. This is, from the theoretical standpoint, a much more complicated process than that of removing the stress. The usual method of annealing glass heretofore has been as follows: The glass is heated at a moderate rate to a temperature at which the strain disappears almost instantaneously (with ordinary crown glass, for example, this temperature would be about 570°), and is then cooled very slowly down to room temperature. The permanent strain acquired by the glass in this case depends on the rate of cooling, and can be calculated fairly closely by equation (5) if h is taken as the *cooling* rate (in deg. C. per minute). Thus, if a plate of glass 3 cm. thick is to be cooled from a high temperature at such a rate that along the middle not more than 5$\mu\mu$ per cm. birefringence is introduced, the cooling rate would be

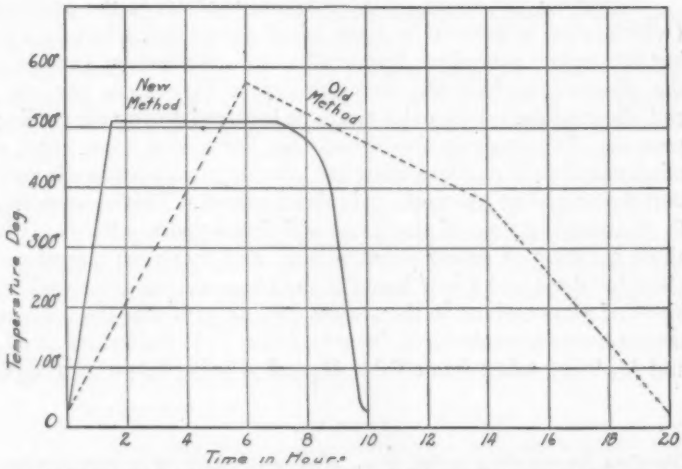
$$\frac{5}{13 \times \left(\frac{3}{2}\right)^2} = 0.17 \text{ deg. per min.}$$

or about 10° per hour. Other things being equal, the cooling varies inversely as the square of the thickness.

So much for the usual method of annealing glass. A procedure which is believed to be much better is as follows: Instead

of heating the glass to a rather high temperature for a short time, we hold it at a much lower temperature for a longer time. In this case the cooling rate can be much greater than with the usual method, a circumstance which compensates for the extra time spent in holding the glass at the annealing temperature. The two methods are compared graphically in Fig. 3. This improved method was used during the war in the annealing of some hundreds of thousands of pounds of glass, and the satisfactory

FIG. 3.



The broken line indicates graphically the usual method for annealing optical glass, and the full line the procedure similar to that recommended in this paper for ordinary crown glass 2 cm. thick. By this newer method the glass is heated very rapidly, is then held for some hours at a rather low annealing temperature, and is then cooled at a rapidly increasing rate.

results obtained indicated that this procedure has many advantages over the ordinary method.

In the first place, it is much easier to hold an annealing kiln at a constant temperature than to cool it at a given constant rate. The newer method requires a fairly constant temperature for some hours, but the subsequent cooling takes place in a short time and does not need careful control, so that on the whole the chances of failure, particularly when unskilled workmen are employed to regulate the burners, are less than with the older method which involves the difficult operation of cooling at a constant slow rate.

Another advantage of annealing at the lower temperature is that it minimizes the danger of overheating the glass. This is of especial importance when annealing valuable optical glass, large batches of which in several cases known to the authors have been spoiled, on account of the fact that the temperature in the annealing furnace was accidentally allowed to become about 50° too high. The sum of the time spent in annealing and the time spent in cooling is somewhat less for the second method, and by the newer method there is a saving of time spent in heating the glass up to the annealing temperature.

Annealing Schedules.—Mathematical analysis of the problem (which is too lengthy to be given here) shows that when following the newer procedure best results are obtained by annealing the glass to one-half the allowable strain (say 2.5$\mu\mu$ per cm.) and allowing the additional 2.5$\mu\mu$ to be incurred during the cooling process. The analysis also shows that for a slab 2 cm. thick a minimum time is required when the annealing temperature is such that the annealing constant, A, is about 0.0038. This corresponds to an annealing time of about one and three-quarters hours. We allow a factor of safety equal to two, and therefore anneal the glass for three and a half hours at the temperatures—for various kinds of glass—given in the second column of Table III. These temperatures are calculated from equation (7), the values of M_1 and M_2 being taken from Table II, and A being taken as 0.0038.

TABLE III.

Directions for annealing optical glass. Heat very rapidly up to annealing temperature; hold for the appropriate time, 3½ hours for plates 2 cm. thick and 12 hours for plates 4 cm. thick; and cool at an increasing rate which except at the start doubles for every 20° drop in temperature.

Kind of Glass.	Annealing temperature for plate 2 cm. thick. Initial cooling rate 24° C. per hour.	Annealing temperature for plate 4 cm. thick. Initial cooling rate 6° C. per hour.
Borosilicate Crown	542	522
Ordinary Crown	515	494
Light Barium Crown	553	534
Heavy Barium Crown	593	578
Barium Flint	495	474
Light Flint	409	391
Medium Flint	419	403
Heavy Flint	408	392
Extra Heavy Flint	382	364

As for the cooling rate, it can be shown that minimum strain is introduced by cooling in a certain specified time if the cooling rate follows the relation

$$h = \frac{h_0}{2}\left(1 + 2^{\frac{\theta_0 - \theta}{20}}\right)$$

in which h_0 is the initial cooling rate, θ_0 is the annealing temperature and θ is any temperature. Except at the beginning this is nearly equivalent to the statement that the cooling rate doubles for every 20° drop in temperature.[9] Furthermore, it so happens that the time spent in cooling is approximately equal to the time required at the annealing temperature.

In the third column of Table III are given the annealing temperatures for a slab 4 cm. thick, and at the head of the second and third columns are given the proper initial cooling rates for the two thicknesses. For the 2 cm. slab the cooling rates in the successive 10° intervals of temperature would be 24° (per hour), 29°, 36°, 46°, 60°, 79°, etc., and for the 4 cm. slab, 6°, 7°, 9°, 12°, 15°, 20°, etc. In general, doubling the thickness of the glass requires a 20° diminution in the annealing temperature, a multiplication by four of the annealing time, and a division by four of the initial cooling rate.

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[9] It is obvious that if the cooling rate be thus increased in geometrical ratio, the rate eventually becomes very great; indeed, so great that the glass would be fractured. It turns out, however, that by the time this excessive rate is reached the temperature would usually be below the annealing range, so that the cooling rate would then be without much effect on the final strain or on the total time required for cooling.

A METHOD FOR DETERMINING THE ANNEALING TEMPERATURE OF GLASS.

BY

J. T. LITTLETON and E. H. ROBERTS.

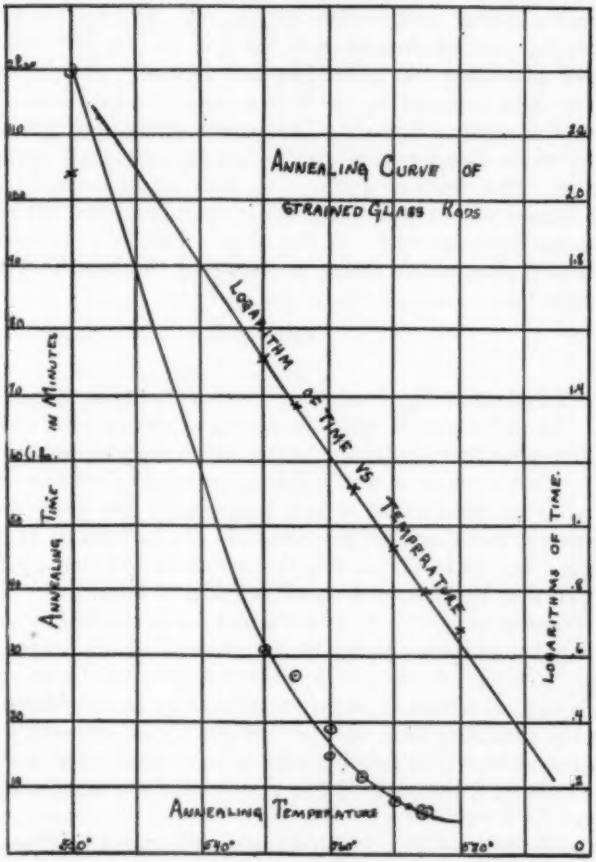
ANNEALING in glass is defined as the process of relieving strains acquired in cooling. The annealing or relaxation temperature is a function of the time, but it is desirable to have this time as short as practical. After the strain has been relieved the glass should be cooled at such a rate as to prevent the acquirement of further strain. Hence in practice, the heat treatment consists of two parts: the first—annealing; the second—the cooling process.

The annealing rate of a glass may be assumed to be proportional to the viscosity of the glass, hence it would be justifiable to measure the annealing temperatures of glasses by means of a viscosity standard. Accordingly, in order to determine the most practical viscosity for annealing, the annealing temperature of a standard glass and form of ware was most carefully determined by inspection in polarized light of glass rods in an electric furnace. These results were then checked by tests on ware. Having established this temperature, it is then necessary to devise some method of measuring the viscosity of the glass at the determined temperature. All glasses which have a viscosity equal to that of the standard glass at the chosen temperature would anneal at the same rate, all dimensions being equivalent. This assumption is not strictly correct but it is sufficiently true for all practical purposes. Hence the problem is resolved into measuring the viscosity of a standard glass at its annealing point and finding the temperature of a glass at which its viscosity is equal to that of the standard glass at its annealing temperature.

The annealing temperature of a glass (to be termed the standard) was determined, as mentioned above, by observing strained glass rods in polarized light, while in an electric furnace. The cold rods were inserted in the furnace of a definite temperature and the time for the strain to be "completely" relieved was noted. This was done at a series of increasing temperatures, thus giving a curve between the temperature and time of annealing. The rods were four centimetres long and one centimetre in

diameter, and were viewed along the axis of the rod. These exhibited three to six wave lengths' retardation, as was shown by the number of rings. The rate of annealing was determined by

FIG. 1.



the rate of disappearance of these rings. Using this as a measure the greater part of the strain would be relieved in a relatively small part of the time necessary to relieve the whole. For this reason the time of complete annealing does not depend a great deal upon the initial strain.

There were other interesting phenomena, such as the formation of what might be called secondary rings having very sharp definition. But since these rings were not studied in any detail, no further description of them can be given. The method given by C. V. Boys,[1] in which mechanically loaded bars were observed through a quartz wedge compensator, was also used, and while the results obtained checked those taken in the way just stated, no decided advantage was secured by this method.

The data obtained by the first method are expressed in the form of a curve (Fig. 1). This curve shows that practically all the strain disappears at 560° C. in approximately seventeen minutes. But, since at 550° C. so little strain could be noted after fifteen minutes of time, this temperature was selected as the annealing temperature of this glass. The data plotted logarithmically give, within limits, as shown by the logarithm curve, a straight line. The equation of this curve is

$$T = 10^{.0289\,(602.-t)}$$

where T is the time for "complete" annealing at the temperature $t°$ C. In order for the glass to anneal in one second, the temperature would have to be 602° C., at which the glass would warp easily. Furthermore, at 500° C. the glass would anneal in sixteen hours. This means that at this temperature the glass was so hard that it would not acquire strain by any process of ordinary cooling. The logic of choosing this point for the strain point is given further verification in work referred to later.

Annealing at 550° C. in fifteen minutes was checked by experiments on actual ware. Hence the conclusion is that a temperature of 550° C. is a good practical annealing temperature for this glass, since a time of fifteen to twenty minutes may be considered as a desirable annealing time, and yet the glass was sufficiently hard so that no softening or warping whatever occurred. The next step was to obtain a measure of the viscosity of the standard glass at 550° C.

The drawing of Fig. 2 shows the apparatus used. The glass cane, ten centimetres long and four to five millimetres in diameter, was sealed between two larger pieces of cane of one centimetre diameter, the ends of which were held in chucks. One chuck was centred on the axis of a ball-bearing pulley wheel, the other to a

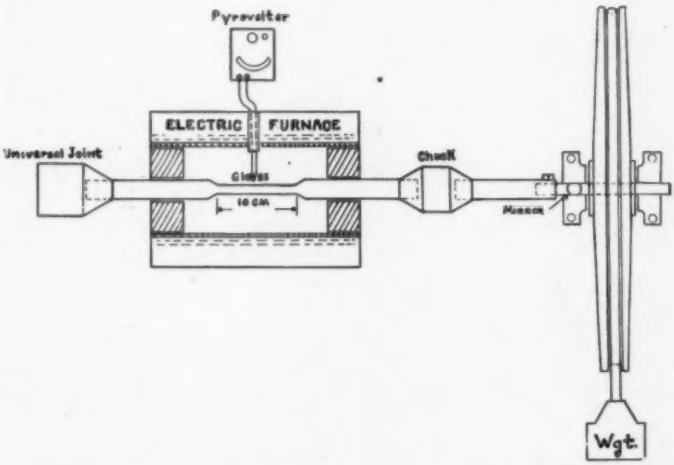
[1] C. V. Boys, *Nature*, p. 150, Oct. 26, 1916.

universal joint. The temperature of the furnace in which the glass was heated was raised at the rate of one or two degrees per minute. This rate could probably be increased. The pulley wheel was loaded at the rim so that a shearing stress of four kilograms per square millimetre was given to the glass, the load being computed from the formula

$$W=\frac{\pi r^3}{2R}T$$

where W is the load, T is the shearing stress, r the radius of the glass cane, and R the radius of the pulley.

FIG. 2.

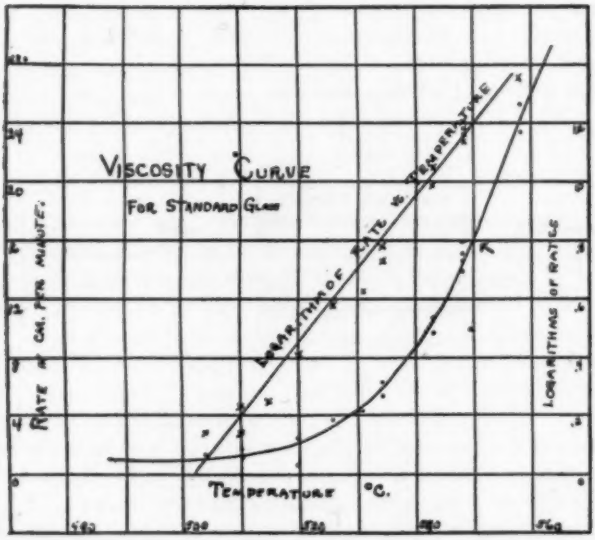


After the rod was inserted in the furnace the load was applied and the position noted of a spot of light reflected from a concave mirror attached to the axis of the wheel and focussed on a scale two metres distant. The rate of motion of this spot was taken as a measure of the fluidity of the glass. The recording of the position of this spot and the temperature of the furnace at various intervals gave values from which a viscosity curve was obtained. This determined the rate of rotation at 550° C. for standard glass to be sixteen centimetres per minute or an angular rotation of 5° 32″ per minute.

Hence to obtain the annealing temperature of any glass, the above experiment is repeated on the glass and the temperature which gives a scale deflection of sixteen centimetres per minute is the annealing temperature of the glass.

Two other very important temperatures are also obtainable from this curve. By plotting the logarithm of the fluidity against the temperature the curve is nearly a straight line. The slope of this curve is a measure of the rate of viscosity change for the glass and its intercept on the temperature axis when the rate of

FIG. 3.



deflection is determined as above, using the same units and rods of the same dimensions, gives a temperature at which the glass takes on very little permanent strain when cooled at any ordinary rate. At this temperature the glass anneals in about sixteen hours. The maximum temperature to which it is safe to heat a glass may be determined by practical tests on the standard glass in the form of ware commonly used. Having determined the maximum temperature, the point on the fluidity curve at that temperature gives a measure of the maximum allowable fluidity. Therefore any glass of a fluidity equal to this standard is at

the maximum safe temperature. The curve for the standard previously given does not extend to this point.

Using these methods the following data were obtained for various Corning glasses:

TABLE I.

Glass.	Annealing Point.	Strain Point.
Borosilicates:		
1.....	518° C.	470° C.
2.....	550	503
3.....	524	472
4.....	522	467
Limes:		
1.....	493	441
2.....	472	412
3.....	523	472
4.....	514	466
Leads:		
1.....	419	364
2.....	451	382
3.....	436	382
4.....	433	353
5.....	429	353
6.....	430	369

The direct application of these data to other glassware can be safely made only when the ware to be annealed is smaller in size than the ware used as a check. If the glass be larger, such as large lenses of optical glass, it will be first necessary to establish the correct annealing conditions for that size of ware, using data obtained above as a guide, and then temperatures for any other glass having the same dimensions can be determined by the torsion experiment on a small sample.

It is practically impossible to determine the correct cooling rate for all forms of glassware made from different glasses except by actual experiment on the ware itself, therefore very little stress has been laid on this important phase of the annealing problem in this paper. Any temperature limits can serve only as a guide except when directly derived from data on glass of a certain size and shape.

Summary.—An experiment has been described which combines annealing temperatures with viscosity measurements in such a manner that the three important annealing temperatures, the maximum, the most practical, and the minimum, can be obtained from the viscosity measurements.

CORNING GLASS WORKS.

1919 REPORT OF THE STANDARDS COMMITTEE ON PHOTOMETRY AND ILLUMINATION.

BY

P. G. NUTTING, Chairman.

THE STANDARDS COMMITTEE ON PHOTOMETRY AND ILLUMINATION submits as its first report a tentative outline of photometric nomenclature, lists of fundamental units and certain fundamental definitions and data. These are based in part upon purely geometrical relations and partly upon physical relations, together with the laws of the reaction of the average human retina to radiation. The fundamental quantity is of course radiation, the fundamental unit flux density (flux per unit area) of that radiation, a unit preserved by means of certain groups of reference standards reserved for that purpose. A summary of the more useful fundamental units is given in the following table constructed to exhibit the essential relations existing between them.

Summary of Photometric Units and Nomenclature.

Nature of the Unit.	Symbols.	Derivation.	Dimensional Relations.	Def. Eqn.	Names of Units.	Relations to Standard.
Quantity.....	Q	$R \times V$	Energy × visibility	Ft	Light-Joule; Lumen-Sec.	SAt
Flux.....	F	Q/t	Power × Visibility	F	Light-Watt; Lumen	SA
Flux Density or Illumination	D	Q/At	$\frac{\text{Flux}}{\text{Area}}$	F/A	Lt. Wt./cm²; Lumen/cm²; Phot., M. C., Ft. C., Lux	S
Exposure.....	E	Q/A	Ill. x time	Ft/A	Phot.-Sec.	St
Concentration, Intensity or Angular Density	C	$Q/\omega t$	$\frac{\text{Flux}}{\text{Solid Angle}}$	F/ω	Lt. Wt./ster.; Lumen/ster.; Candle	SA/ω
Brightness or Surface Density of Angular Density	D	$Q/\omega At$	$\frac{\text{Flux Density}}{\text{Solid Angle}}$	$F/\omega A$	Lt. Wt./cm²/ster.; Lumen/cm.²/ster.; Lambert	S/ω

This table is self-explanatory. The symbols used are unofficial; they are chosen merely for algebraic simplicity in elucidating

relations between quantities. The first four units have long been in common use by illuminating engineers. The Concentration of a beam of light is its Angular Flux Density, to which the Intensity of the equivalent point source is, in a sense, equivalent. Brightness, or the Surface Density of Angular Flux Density, is a proper measure of the radiation (or light) from one unit normal area to another unit normal area and is directly applicable to what is sensed as brightness, and more generally to the field and zone pencils of a beam of light through a lens system. With a system of units as above outlined, it does not appear necessary to employ different units in specifying incident and emitted radiation.

Three systems of units based on the relations outlined above are suggested for consideration and possible adoption by the society: (1) A system of radiation units for dealing with radiant energy; (2) a rational system of photometric units for use in theoretical problems (*e.g.*, in pyrometry) involving both radiant energy and luminosity; and (3) a practical system of photometric units for dealing only with light in terms of light units and light standards.

I. RADIATION UNITS.

Nature of the Unit.	Symbol.	Dimension.	Unit.
Quantity	$Q = Ft$	Radiant Energy	Joule.
Flux	F	Radiant Flux	Watt.
Flux Density	$D = dF/dS$	Flux Density	Watt per cm².
Exposure	$E = Dt$	Energy Density	Joule per cm².
Concentration of Flux	$C = dF/dw$	Flux per unit Solid Angle	Watt per steradian.
Concentration Density	$B = dC/dS$	Flux Density per unit Solid Angle	Watt per cm² per steradian.

II AND III. PHOTOMETRIC UNITS.

Nature of the Unit.	Symbol.	Dimensions.	Rational System.	Practical System.
Quantity	Q	Luminous Energy	Light-watt-second	Lumen-second.
Flux	F	Luminous Flux	Light-watt	Lumen.
Flux Density	D	Luminous Flux Density	Light-watt per cm²	Lumen per cm² (Phot).
Exposure	E	Luminous Energy Density	Light-watt-second per cm²	Lumen-second per cm² (Phot Sec.).
Intensity	C	Luminous Angular Density	Light-watt per ster. (pyr)	Lumen per ster. (candle).
Brightness	B	Luminous Flux Density of Angular Density	Light-watt per cm² per ster. (pyr) per cm²	Lumens per cm² per ster. (candle per cm².

The units of the Rational System are those of the corresponding radiation system multiplied by the Visibility of radiation.

The units of the Practical System are those of the Rational System multiplied by the Luminous Equivalent of radiation, in lumens per watt.

The relation between the various photometric units of the practical system are as follows:

IV. RELATIONS BETWEEN PRACTICAL UNITS.

1 lumen is emitted by a source of 0.07958 spherical candlepower.
A source of 1 spherical candlepower emits 12.57 lumens.
1 lux = 1 lumen incident per square metre = 0.0001 phot = 0.1 milliphot = 100 microphots.
1 phot = 1 lumen incident per square centimetre = 10,000 lux = 1,000 milliphots = 1,000,000 microphots.
1 milliphot = 0.001 phot = 1,000 microphots = 0.929 foot-candle.
1 foot-candle = 1 lumen incident per square foot = 1.076 milliphots = 10.76 lux.
1 lambert is the brightness of a surface emitting 1 lumen per square centimetre of projected area in the direction considered.
1 millilambert = 0.001 lambert = 1000 microlamberts.
1 lumen per square foot emitted by a perfectly diffusing surface produces a brightness of 1.076 millilamberts.
1 millilambert is the brightness of a surface emitting 0.929 lumen per square foot of projected area in the direction considered.
1 lambert = 0.3183 candle per square centimetre = 2.054 candles per square inch.
1 candle per square centimetre = 3.1416 lamberts.
1 candle per square inch = 0.487 lambert = 487 millilamberts.

Certain quantities much used in dealing with both light and radiation involve only ratios of similar quantities and are therefore expressible as pure numbers. These are the following:

V. NUMERICAL RATIO UNITS.

Emissivity = ratio of emission to that of a black body at the same temperature.
Reflectivity = ratio of reflected to incident light or radiant energy.
Absortivity = ratio of absorbed to incident light or radiant energy.
Transmissivity = ratio of transmitted to incident light or energy.
Opacity = 1/Transmissivity.
Density = $\log_{10}$ Opacity = $-\log_{10}$ Transmissivity.
Specific Density = Density per unit thickness.
Scatter = Apparent Density (specular light) — True Density.

Photovisual Relations.—The ratio of light to radiant energy, the Luminous Equivalent of Radiation, is a function of wave length determinable only by experiment. Its absolute value—

approximately 660 lumens per watt at its maximum wave length .556μ—is still uncertain by at least 5 per cent. Its relative value, the Visibility of radiation, is much more accurately known. The data of the following table are averages for about 200 subjects having normal vision. The absolute visibilities given were calculated from the relative on the assumption of 667 lumens per watt or 0.0015 watt per lumen.

VI. VISIBILITY OF RADIATION.

Average Normal Eye.

	Wave Length ($\mu\mu$)	Relative to that at 556 ($\mu\mu$)	Absolute Visibility
	400	0.0004	0.27
	10	.0012	0.80
	20	.0040	2.7
	30	.0116	7.72
	40	.023	15.3
	450	0.038	25.3
	60	.060	40.0
	70	.091	60.7
	80	.139	92.6
	90	.208	139
	500	0.323	216
	10	.484	322
	20	.670	446
	30	.836	557
	40	.942	629
	550	0.993	662
	60	.996	663
Average	70	.952	641
Normal	80	.870	580
Eye	90	.757	502
	600	0.631	421
	10	.503	336
	20	.380	253
	30	.262	175
	40	.170	113
	650	0.103	68.8
	60	.059	39.3
	70	.030	20.0
	80	.016	10.7
	90	.0081	5.4
	700	0.0041	2.7
	10	.0021	1.4
	20	.0010	0.67
	30	.00052	0.35
	40	.00025	0.17
	750	0.00012	.08
	60	.00006	.04

The utility of illumination depends upon the mean brightness of the view provided by it and the variation of brightness within that field. The average brightness of the field viewed, through automatic psychophysical adjustments within the eye itself, determines (1) the absolute sensibility of the retina and hence the intensity of the brightness sensation, (2) the minimum contrasts perceptible, (3) the maximum (glaring) brightness just tolerable, and (4) pupillary diameter. Data on these quantities, based on the observations of from three to eight experienced observers, are given below for the entire range of brightnesses within which the retina is operable.

VII. SENSIBILITY AND BRIGHTNESS.

Average Brightness of Field Viewed.	Relative Sensibility of Retina.	Contrast Sensibility Relative to Maximum.	Minimum Glaring Brightness of Field.	Diameter of Pupil.
0.000001 ml.	0.77	0.017	20.1 ml.	7.4 mm.
0.00001	0.17	0.026	40.7	7.3
0.0001	0.038	0.043	89	7.2
0.001	0.0077	0.078	186	7.0
0.01	0.0018	0.22	400	6.7
0.1	0.00041	0.46	810	6.0
1.0	0.000087	0.83	1660	5.0
10.0	0.000020	0.98	3470	3.8
100	0.0000037	1.00	7250	2.7
1000	0.00000033	0.72	14450	2.1
10000	(0.000000003)	0.36	30900	2.0

Brightness values are in millilamberts. General sensibility is relative to that at the absolute threshold (about 0.000000 70 m.l.) taken as unity. The minimum glaring brightness is that just uncomfortably bright to an eye adapted to the brightness of the first column. The diameter of pupil is that for the case of both eyes open. This diameter determines not only retinal flux density but the ultimate limit of resolving power. Contrast sensibility is relative to that at its maximum at ordinary intensities. All sensibilities are referred to normal pupil and normal adaptation, zero for intensity sensibility and glare and about one minute for contrast.

These data apply for equal luminous brightnesses, to all wave lengths. For different individuals having normal vision, the variation is probably not over 5 per cent. from the mean. Brightness sensibility is proportional to the inverse $\frac{2}{3}$ power of the

brightness of the field viewed, $B \times F^{\frac{2}{3}} = \text{constant}$. The minimum brightness producing a sensation of glare is $1700 \times$ the cube root of the field brightness, $G = 1700\, F^{\frac{1}{3}}$. The increment in brightness represented by the contrast sensibility fraction is equal to the unadapted threshold limen. Flux density at the retina in lumens per cm.^{2} $= 0.134 \times 10^{-5} \times$ area of pupil in mm.^{2} $\times$ brightness of field viewed in millilamberts.

1919 REPORT OF THE STANDARDS COMMITTEE ON LENSES AND OPTICAL INSTRUMENTS.

BY

C. W. FREDERICK, Chairman.

THIS first report of the Standards Committee on Lenses and Optical Instruments deals with single lens combinations only. It covers the classification of the various types of lenses, the limits of performance specifications, standards of performance and tolerances. Subsequent committees will doubtless find further revision necessary, and many other portions of this field remain to be covered.

I. NOMENCLATURE AND CLASSIFICATION.

Photographic Objectives.

Objectives	Aperture Ratio	Focal Lengths	Field Angle
Cinematograph	F/1.9, F/3.5, F/4.5	2, 4, 6″	7½, 15, 20°
Portrait	F/4.5, F/5.6	6–12″	12–20°
Speed Ordinary	F/5.6, F/6.3	4–12″	25–30°
Ordinary	F/6.3, F/8	4–12″	25–35°
Process	F/8 Down	8–24″	27–30°
3-Color Process	Same, but achromatized for red, green and blue.		
Wide Angle	F/8 Down	3–6″	40–55°
Meniscus	F/14 Down	3–6″	15–25°
Rapid Rectilinear	F/8 Down	3–8″	20–25°
Telephoto	F/8 Down	8–20″	10–20°
Airplane	F/4.5–F/10	10, 24, 48″	15–25°
Astro. Refractor	F/6.3–F/32	24–72″	5– 7°
Astro. Reflector	F/4.5–F/10	36–100″	2– 5°

Telescope Objectives (Visual).

Reading telescopes and collimators	F/6 –F/12	4–20″	1–3°
Position observing telescopes	F/10–F/18	20–40″	1–2°
Ordinary observing telescopes	F/15–F/20	36–720″	1–3°

Microscope Objectives.

	Numerical Aperture	E. F. L.	Working Distance
Ordinary 48	0.08	48 mm.	53 mm.
32	0.10	32	38
16	0.25	16	·7
8	0.50	8	1.6
4	0.6–0.9	4	0.3–0.6
Oil Immn. 1.9		1.9	0.13–0.15

Oculars, Numerous Types	5–50 mm.	E. F. L.	1–3° field
Projection Lenses, Numerous Types ..	2–18″	E. F. L.	1–15° field
Condensers F/0.5–F/1	1–6″		.....
Magnifiers F/2–F/3	5–25 mm.		1–3° field

II. LIMITS OF PERFORMANCE SPECIFICATIONS.

The definition given by any lens operating with zone and field pencils of but small to moderate aperture (1:8 or 7° in extreme angle) should approach theoretical resolving power, *i.e.*, the diffusion in the image of any line or point source equal to ratio of focal length to aperture of lens times wave length of light used (diffusion $\delta/\lambda = F/D$). Thus for an F/10 lens using green light the diffusion in the image should not be much over 0.005 mm. The objectives of telescopes for visual observation fall in this class. Lenses of wider aperture (F/2 – F/4.5) may be designed to give from 1/5 to 1/2 their theoretical resolving power over a limited field (5 – 20°). Wide angle lenses with small apertures may also give from 1/5 to 1/2 their theoretical resolving power over a wide field.

In photographic objectives with which negatives and prints are to be made to be viewed by the eye the definition required is not greater than the resolving power of the eye, which is half a minute of arc or 0.033 mm. at 10 inches. In motion picture film, the lower limit of tolerance in diffusion is such as corresponds to 3 mm. on the screen, or 0.03 mm. in the projected negative. The screen tolerance is half the resolving power of the eye at 35 ft. In oculars the limiting tolerance is again the resolving power of the eye, $t = f/7500 = 0.003$ mm. for an ocular of 25 mm. focal length f. If the oculars give stigmatic zone pencils, the eye can accommodate to considerable departure from a plane image. The permissible departure is $f^2/$ accommodation or $f^2/1000$ for 1 diopter.

III. TOLERANCES IN LENS TYPES.

	Confusion Tolerances Lower Bogey Upper	Stigmatic Tolerances Normal to Focal Plane (Color, Zone and Field)	Distortion.
Process lenses.....	0.01 0.02 0.04 mm.	0.16 0.32 0.64 at $F/16$	$0.0002\,f$
Cinematograph lenses	0.02 0.03 0.05	0.06 0.10 0.15	$0.0005\,f$
Landscape lenses.....	0.03 0.05 0.10	Bogey 0.4 at $F/8$	$0.0005\,f$
Portrait lenses.....	0.10 0.20 0.30	Bogey 1.0 mm.	$0.0010\,f$
Telescope objectives..	Theoretical resolving	power $\delta = 2f\lambda/D$ $\delta V =$	f^3/D^2
Micro objectives.....	½ to ¼ theoretical resolving power.		
Oculars.....	$\delta = f/7500$	$\delta V = f^2/A$	
Condensers.....	Uniform illumination	required, not definition.	

Other Standards.—In single lens combinations there remain to be specified various tolerances in definition as affected by wave length, zone angle and field angle, individual Seidel aberrations, standard screw threads, tables of standard glass types and of glass combinations. In combinations of lenses in complete optical instruments such as telescopes, microscopes, field glasses, periscopes, sextants, telemeters, sights, transits, spectrometers, refractometers, spectrophotometers, goniometers, polarimeters, etc., types remain to be classified, limits of performance specified in resolving power, sensibility range, field, etc. It is recommended that such specifications be undertaken by subsequent committees.

THE STANDARDS COMMITTEES OF THE OPTICAL SOCIETY OF AMERICA.

BY

P. G. NUTTING.

ONE of the more important specific objectives of the Optical Society is the development of Technical Optics. Perhaps the greatest need in that field is for broad and authoritative works of reference, outlining the best practice as regards instruments and methods and giving the best standard data available. Private enterprise has failed to provide such aside from a few scattered books of varied character. It is the obvious function of a technical society, such as ours, to foster the preparation of reference material of a uniform high quality covering the entire field covered by the society. The direct method of attack is through a series of carefully selected standards committees. Such committees, with personnel gradually changing from year to year and publishing reports from time to time, may be expected in five to ten years to accumulate the material desired.

This work was initiated during 1919 by the appointment of a general committee on Nomenclature and Standards organized in nine sub-committees reporting at the annual meeting. While these reports were necessarily of a preliminary nature and fragmentary in character, they were an indication of what could be accomplished and of the earnest support to be expected of the Society. The Executive Council has accordingly made plans to continue and extend this work through the Standards Committees listed below. Each committee will be expected to cover at least the ground indicated; the personnel of these committees is in the hands of President Richtmyer.

1. *Colorimetry.*—Nomenclature. Instruments and Methods. Standard Data on Hue, Saturation and Brightness Sensibility and Scales for the average normal Human Eye. Spectral Energy of Standard White. Standard Transformation Data between Monochromatic, Trichromatic, Rotary Dispersion and Spectrophotometric Specifications. Reference Standards of Color. Progress during 1920. Bibliography.

2. *Lenses and Optical Instruments.*—Classification. Nomenclature. Standards of Performance. Tolerance. Precision and

Factory Testing Instruments and Methods. Standard Screw Threads. Lens Materials. Lens Theory. Methods of Computation, Notation and Tables of Data. Special Instruments, Standards of Performance and Tolerances. Progress during 1920. Bibliography.

3. *Optical Glass.*—Nomenclature of Glass Types, Specification and Listing of Technical Glasses. Standard Specifications of Quality, Tolerance, Testing Instruments and Methods. Progress during 1920. Bibliography.

4. *Photographic Materials.*—Classification of Standard Types of Plates, Films and Papers. Standards and Tolerances in Speed, Contrast, Latitude, Development Factor. Standard Developers, Fixing Baths, Toning Solutions, Sensitizing Baths. Progress during 1920. Bibliography.

5. *Photometry and Illumination.*—Nomenclature. Fundamental Relations, Photometric Units. Instruments and Methods for Photometry, Microphotometry, Comparison Photometry, Illuminometry. Theory of Sensibility. Standards and Tolerances in Illumination. Standard Visibility Data, Standard Contrast Sensibility Data, Standard Adaptation Data. Sources of Illumination, Diffusing Media, Diffusion Photometry. Progress during 1920. Bibliography.

6. *Polarimetry.*—Standard Instruments and Methods. Reference Standards and Tolerances. Theory of Sensibility and Precision. Precision and Tolerances in Technical Testing. Progress during 1920. Bibliography.

7. *Projection Apparatus.*—Nomenclature, Projection Lenses and Instruments. Standards and Tolerances. Illumination Standards and Tolerances. Definition, Field and Flicker Standards and Tolerances. Progress during 1920. Bibliography.

8. *Pyrometry.*—Instruments and Methods. Nomenclature. Radiation Constants and Formulas. Standard Data on Non-black Radiation and Temperature. Data on Standard Light Filters. Progress during 1920. Bibliography.

9. *Reflectometry.*—Nomenclature. Instruments and Methods. Reflecting Power Standards. Progress. Bibliography.

10. *Refractometry.*—Standard Instruments and Methods. Standards of Precision and Technical Testing. Air Correction Tables and Formulas. Standard Wave Lengths. Comparison Standards. Birefractometric Instruments and Methods. Progress. Bibliography.

11. *Spectacle Lenses.*—Nomenclature. Units. Standard Types. Standard Specifications and Tolerances. Standard Materials. Standard Dimensions and Forms. Instruments and Methods for Precision and for Technical Testing. Progress during 1920. Bibliography.

12. *Spectrophotometry.*—Standard Instruments and Methods. Nomenclature. Classification of Instruments and their Applications. Approved Standard Sources. Specification of Data. Fundamental Relations and Constants in Density and Concentration. Tolerances in Wave Length and in Transmission and Reflection. Progress during 1920. Bibliography.

13. *Spectroradiometry.*—Standard Radiometers and Radiometric Methods. Spectral Absorption of Standard Lens and Prism Materials. Standard Data on Spectral Emission, Absorption and Reflection of Specific Materials. General Theory. Formulas and Constants of Radiation. Progress during 1920. Bibliography.

14. *Visual Sensitometry.*—Approved Instruments and Methods. Nomenclature. Units, Formulas, Constants and Standard Data on (1) The Visibility of Radiation, (2) Intensity and Contrast Sensibility, (3) Chromatic Sensibility, (4) Rates of Adaptation, and (5) Absolute Sensibility. Progress during 1920. Bibliography.

15. *Wave Lengths.*—Approved Standard Instruments and Methods. Tables of Standard Data and Probable Errors. Air Correction Tables and Formulas. Primary Standards. Comparison Standards. Progress during 1920. Bibliography.

From this list and outline of proposed activities, the scope and depth contemplated may be judged. It is planned to build up from year to year the material for a standard reference text in each sub-field, avoiding controversial matter and matter of little consequence beyond individual preference. Such texts should cover not only nomenclature, fundamental theory and standard data, but standard instruments and methods, sensibility, reference standards and a full bibliography of each subject.

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